# SolarSoft XRT Analysis Guide

## Hinode X-Ray Telescope


| Author | Date | Version Number |
|---|---|---|
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# Contents

# 1 Introduction

This document consists of a Software Guide (Section 2) and Instrument Guide (Section 3). The Software Guide describes how to analyze XRT data; the Instrument Guide gives a broad overview of the X-Ray Telescope's hardware components.

## 1.1 Hinode and the X-Ray Telescope

Hinode is a joint mission between the space agencies of Japan, United States, Europe, and United Kingdom. The craft carries three instruments, a Solar Optical Telescope (SOT), Extreme Ultraviolet Imaging Spectrometer (EIS) and X-Ray Telescope (XRT); together, they are designed to provide multi-wavelength data from the photosphere to the upper corona. The 875-kg craft was launched on September 23, 2006 into a polar, sun-sychronous orbit at 600 kilometers with an inclination of -98°, allowing 9 months of continuous observations and a 3-month eclipse season. Hinode provides approximately 7 GB of data daily.

The XRT images coronal plasmas from 1 to approximately 20 million K with $2''$ resolution ($\approx 1''$ pixels). The XRT images through nine x-ray filters using two filter wheels. The XRT also contains a visible light optic that takes G-band images for alignment. The back-thinned CCD has $2048\times2048$ pixels and images over a $35' \times 35'$ field of view, though partial frame images of various sizes can be read from select areas of the CCD. XRT takes approximately 0.7 GB of data daily as lossless or one of nine forms of lossy JPEG compression.

The baseline duration of the mission is 3 years. Currently XRT, SOT and EIS are operated from the Institute of Space and Astronautical Science (ISAS) in Sagamihara, Japan. See the Instrument Guide (Section 3) for more information.

### 1.1.1 Synoptic Data

The Hinode craft points at sun center for 10 minutes 2-4 times a day, enabling XRT to take synoptic data in the form of full-resolution, full-disk images with both long and short exposures in one or more X-Ray filters. The long and short exposures are taken to capture the dynamic range of the coronal plasma's X-Ray emission and thus the saturated pixels from the long exposure are replaced with corresponding pixels in the short exposure pair. The pair is then available as one image in a form referred to as Level 2 data (See Section 1.2.2).

### 1.1.2 Eclipse Season

The Hinode craft is in a polar, sun-sychronous orbit at 600 kilometers with an inclination of -98°, allowing 9 months of continuous observations and a 3-month eclipse season. The eclipse season begins in May every year; eclipse durations are shown in Figure 1. Effects of atmospheric absorption will be visible in XRT images beginning $\approx$ 4 days before the season through to $\approx$ 4 days after the season, for a total of $\approx$ 100 days.

## 1.2 Overview of the Data Analysis Pipeline

### 1.2.1 Data Transport

XRT downlinks 15 times daily at the Svalbard Ground Station, a member of the Norwegian Space Centre (NSC). Downlinks also occur up to four additional times daily at any one of the Japanese Aerospace Exploration Agency (JAXA) ground station network antennas, which include two Japanese sites, in the Kagoshima and Ibaraki prefectures, as well as three overseas sites: Maspaolomas, Canary Islands, Perth, Australia, and Santiago, Chile. Downlinked XRT telemetry is sent to the ISAS mission archive, the principal XRT data site, for reformatting to create Level 0 data. Both QuickLook and Level 0 data are then mirrored to the Smithsonian Astrophysical Observatory (SAO), in Cambridge, MA. Using the data retrieval techniques described in Section 2.1, users access machines at SAO to obtain XRT data.

### 1.2.2 Data Products

XRT data is available as FITS files, each of which include a data array and a metadata structure array containing a list of keywords (see Appendix 1). Several types of data products are available: QuickLook, Level 0, Level 1, and Level 2.

QuickLook data are expedited to ISAS so XRT operation team members can view images a few hours after the data has been taken. However, these data have not been completely reformatted and thus the images may not be whole and the FITS keywords will not be populated completely or correctly. XRT team members use this data to make operations decisions but these data products are not suitable for scientific purposes.

Level 0 data contains whole images; in addition, the FITS keywords have been populated correctly by the reformatter. Level 0 data cannot be created until all the housekeeping data for a particular observation has arrived at ISAS, which may take up to 7 days. Level 1 data has been calibrated by **xrt_prep.pro** and has units of instrumental Data Numbers. Level 2 data has been further processed into more physical units or into movies. The following table describes each of the XRT data products:

| **Level** | **Pixel values** | **File format** | **Purpose** |
|---|---|---|---|
| QuickLook | Data Number (DN) | FITS | Operations, Data Verification, QuickLook movies |
| 0 | DN | FITS | Basic science |
| 1 | DN/sec | FITS | Calibrated images |
| 2 | Physical units | Any | Short and long exposures summed into one image; Differential Emission Measure; Temperature Maps |

XRT instrument data are available as single Level 0 FITS files with names in the the format **XRTYYYYMMDD_HHMMSS.S.fits**. The files stored in directories organized by hour beneath directories organized by day, month, and year. An example of a directory structure to access an individual FITS file is as follows: **YYYY/MM/DD/Hhh00/**, or **2007/05/27/H1300**.

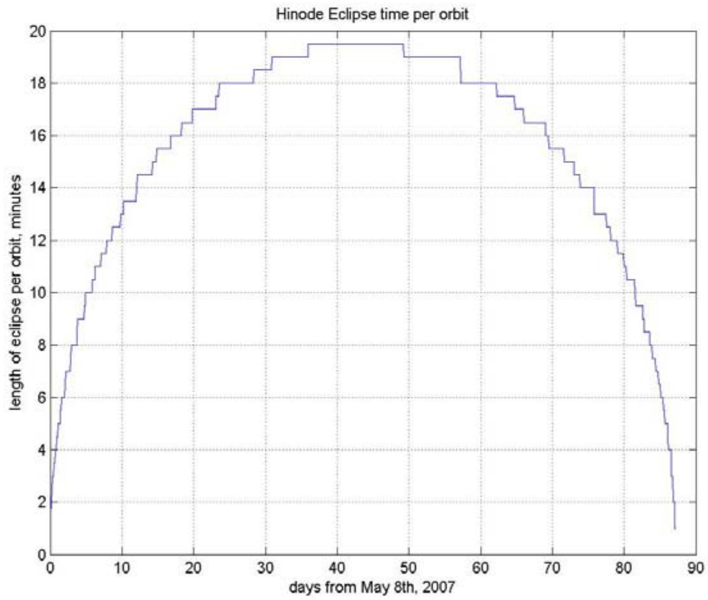



Figure 1: Hinode eclipse season

### 1.3 References

Reference for the XRT Instrument paper:
Golub, L. et al. 2007, Sol. Phys., in press.

Reference for the XRT Camera paper:
Kano, R. et al. 2007, Sol. Phys., in press.

XRT images in the popular media should be credited to SAO, NASA, JAXA, and NAOJ.

### 1.4 Contacts

For data analysis problems, contact `xrt_manager[at]cfa.harvard.edu`.

For science discussions, contact `xrt_science[at]cfa.harvard.edu`.

### 1.5 Acknowledgements

The XRT Analysis Guide was prepared by Monica Bobra with help from Mark Weber and other members of the XRT team.

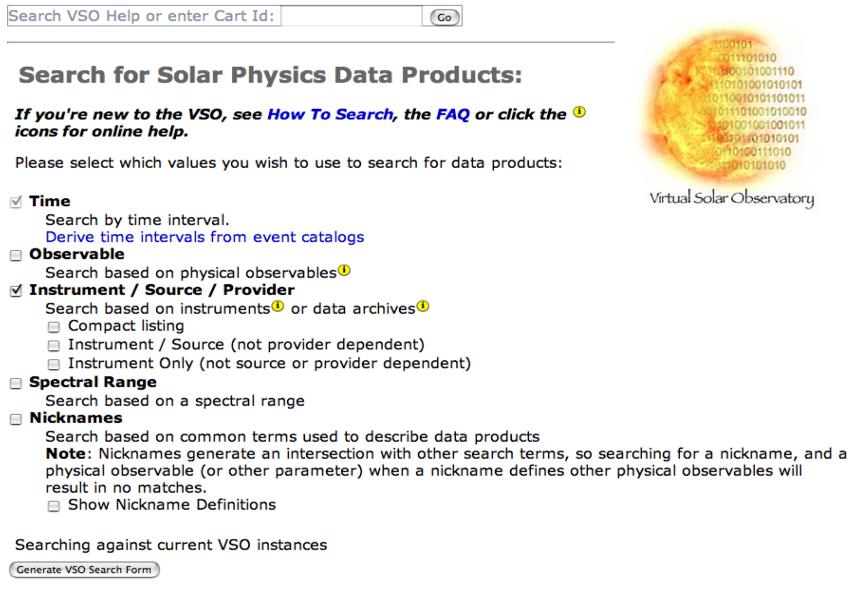



Figure 2: Main VSO search screen

# 2 Software Guide

This section outlines how to analyze XRT data using software publicly available as part of SSWIDL (to add an instrument path to a SSWIDL tree, see `http://www.lmsal.com/solarsoft/`). This process involves obtaining, searching, reading, calibrating, co-aligning and writing XRT data, as well as constructing Level 2 data products such as long-short composite images and various temperature analyses.

## 2.1 Obtaining XRT Data

### 2.1.1 Virtual Solar Observatory via SAO Webserver

Hinode XRT data can be accessed online via the Virtual Solar Observatory (`http://sdac.virtualsolar.org/cgi-bin/search`). Figure 2 shows the main VSO search screen.

Checking the **Instrument/Source/Provider** box creates a form to search specifically for XRT data. The other catagories of interest to XRT data users are **Observables** (for XRT, this is **Intensity**), **Spectral Range** (soft x-rays [1-100A]), and **Nickname** (Soft X-ray image). Once desired catagories have been selected, click the **Generate VSO Search Form** button.

The VSO generated search form is displayed in Figure 3. Once the time and instrument has been selected, choose the **Search** button underneath the date. (HINT: To change the date, change both years first, then both months, then both days. Otherwise the dates will automatically readjust.)

Data for the dates of interest will appear in a form as seen in Figure 4. There are 3 ways to select data. (1) Click on the check box in the first column next to the data entry. (2) Use

VSO Time / Instrument Search Form

Version 1.4

Start Date/Time: 2007 Apr 24 / 00 : 00

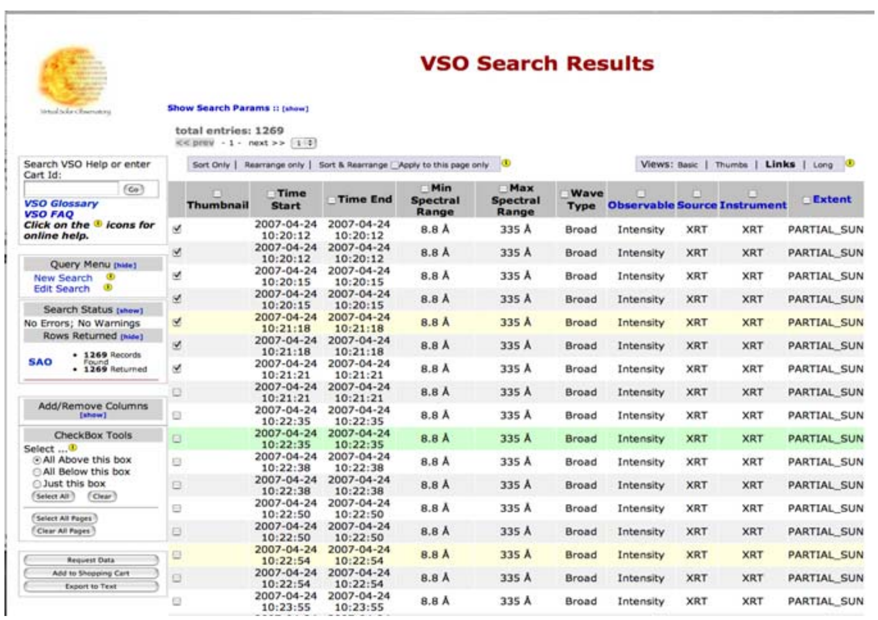
End Date/Time: 2007 Apr 24 / 23 : 59

All Month All Day

Search Clear

| All from Provider | All from | Source | Instrument | Date Range |
|---|---|---|---|---|
| HANET | | BBSO | BBSO | 2000.07.05 → |
| | | KANZ | KANZ | 2001.02.07 → |
| | | OACT | OACT | 2002.02.26 → |
| | | OBSPM | OBSPM | 2004.10.22 → |
| | | YNAO | YNAO | 2000.11.27 → |
| HAO | | MLSO | chp | 1996.04.20 → |
| | | | dpm | 1994.02.20 → |
| | | | mk4 | 1998.10.01 → |
| LSSP | | RHESSI | RHESSI | 2002.02.12 → |
| MSU | | YOHKOH | BCS | 1991.09.01 – 2001.12.14 |
| | | | HXT | 1991.09.03 – 2001.12.14 |
| | | | SXT | 1991.09.03 – 2001.12.14 |
| | | | WBS | 1991.09.01 – 2001.12.14 |
| MWSPADP | | MtWilson | 60-ft SHG | 1915.08.10 – 1985.12.31 |
| NGDC | | GOES-12 | SXI-0 | 2001.09.10 → |
| NSO | | Evans | spectroheliograph | 1996.02.05 – 1999.05.28 |
| | | GONG | Big Bear | 2005.04.11 → |
| | | | Cerro Tololo | 2005.02.24 → |
| | | | El Teide | 2005.02.25 → |
| | | | Learmonth | 2005.02.25 → |
| | | | MERGED GONG | 2001.07.22 → |
| | | | Mauna Loa | 2005.04.11 → |
| | | KPVT | 512-channel magnetograph | 1974.02.01 – 1993.04.10 |
| | | | spectromagnetograph | 1992.04.19 – 2003.09.21 |
| | | McMath | solar fts spectrometer | 1976.03.31 – 2002.08.11 |
| | | O-SPAN | O-SPAN | 2002.12.11 → |
| | | SOLIS | vsm | 2004.01.02 → |
| OBSPM | | Nancay | Decametric Array | 2003.03.10 → |
| | | | Radioheliograph | 1996.10.20 → |
| | | OBSPM | Meudon Spectroheliograph | 1995.12.01 → |
| | | Pic du Midi | Coronagraph | 1995.10.20 → |
| OVRO | | OVRO | OVSA | 2000.03.16 → |
| SAO | | Hinode | XRT | 2006.10.23 → |
| SDAC | | SOHO | CDS | 1996.01.19 → |
| | | | CELIAS | 1995.12.02 → |

Figure 3: Search Form



VSO Search Results

Show Search Params :: [show]

total entries: 1269

<< prev - 1 - next >> 1

Search VSO Help or enter Cart Id: Go

VSO Glossary

VSO FAQ

Click on the icons for online help.

Query Menu [hide]

New Search

Edit Search

Search Status [show]

No Errors; No Warnings

Rows Returned [hide]

SAO • 1269 Records Found • 1269 Returned

Add/Remove Columns [show]

CheckBox Tools

Select ...

All Above this box

All Below this box

Just this box

Select All Clear

Select All Pages

Clear All Pages

Request Data

Add to Shopping Cart

Export to Text

Sort Only | Rearrange only | Sort & Rearrange | Apply to this page only

Views: Basic | Thumbs | Links | Long

| Thumbnail | Time Start | Time End | Min Spectral Range | Max Spectral Range | Wave Type | Observable | Source | Instrument | Extent |
|---|---|---|---|---|---|---|---|---|---|
| | 2007-04-24 10:20:12 | 2007-04-24 10:20:12 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:20:12 | 2007-04-24 10:20:12 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:20:15 | 2007-04-24 10:20:15 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:20:15 | 2007-04-24 10:20:15 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:21:18 | 2007-04-24 10:21:18 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:21:18 | 2007-04-24 10:21:18 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:21:21 | 2007-04-24 10:21:21 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:21:21 | 2007-04-24 10:21:21 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:35 | 2007-04-24 10:22:35 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:35 | 2007-04-24 10:22:35 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:38 | 2007-04-24 10:22:38 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:38 | 2007-04-24 10:22:38 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:50 | 2007-04-24 10:22:50 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:50 | 2007-04-24 10:22:50 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:54 | 2007-04-24 10:22:54 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:22:54 | 2007-04-24 10:22:54 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |
| | 2007-04-24 10:23:55 | 2007-04-24 10:23:55 | 8.8 Å | 335 Å | Broad | Intensity | XRT | XRT | PARTIAL_SUN |

Figure 4: VSO Form

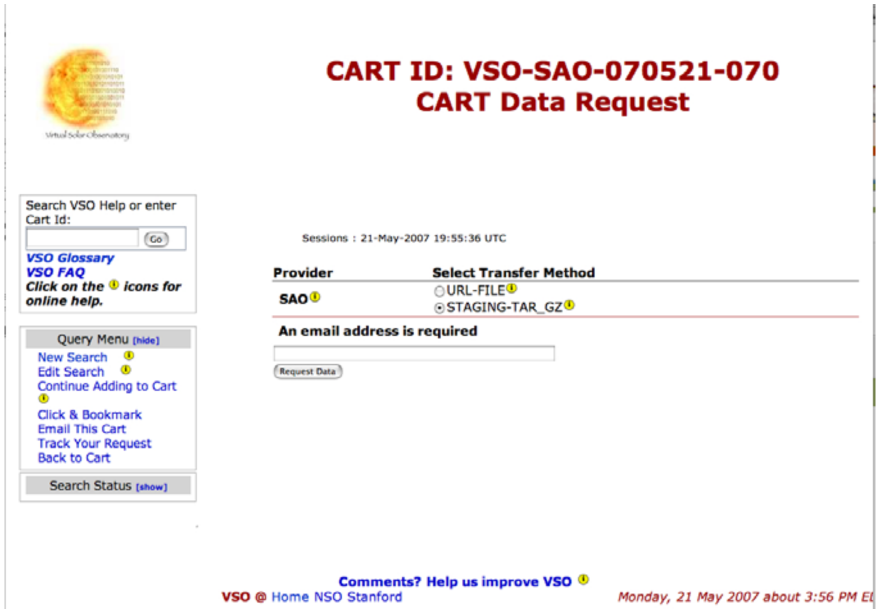



Figure 5: Downloading data

the box on the left column to click **Select All Above This Box**. (3) Use the box on the left column to select **Select All Below This Box**. Finally, click on the **Request Data** button.

Data can be downloaded via a URL or by creating a .tar file that will place the requested files in a staging area (see Figure 5). If you select the second option, you will need to enter an email address. *Please note the instructions on this page and check the current Hinode Data thesis projects before publishing results.*

### 2.1.2 Lockheed Martin SOT Website

Hinode XRT data may also be collected from the LMSAL SOT/XRT Data Center pages (`http://sot.lmsal.com/sot-data`).

There are multiple ways to search for data. Several links to different pages exist, including: **Planned, Recent, Popular, Recommended, Search, and Help**. The **Planned** link contains a listing of the expected observations for XRT and SOT, with an outline of the data to be collected. **Recent** is a listing of data collected with an outline of the different observations for a particular observing run. By clicking on the example image, a link to the datasets for the observation program is created. From this page QuickLook movies can be viewed by clicking on the images, or the data may be retrieved by selecting **Get All Data**. Additional information about the supporting instruments for the observations, the field-of-view and total number of images per filter are also provided. An example of this form is shown in Figure 6.

The additional pages provided at the main page provide different routes to the data; each page is equipped with explanations.

**Search** is a link to the SolarSoft Catalog search engine. This page will permit selection of XRT images from numerous criteria. The different fields may be filled out and when the form is completed the data will be packaged in to a tape archive file and a link to an anonymous FTP

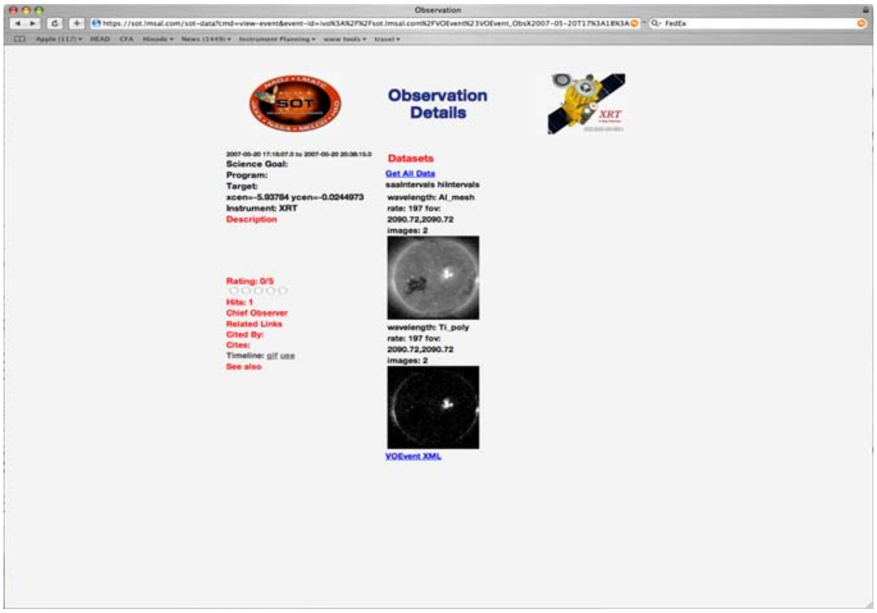



Figure 6: Example LMSAL search form

site will be emailed to the scientist making the data request. This page is shown in Figure 7.

## 2.2 Searching XRT Data with the XRT Catalog

The XRT catalog contains a subset of XRT FITS header keywords, (such as field of view, filter positions, and image type), for every XRT observation. Using the catalog is a useful way to search data without downloading any of it. The catalog may be read and listed using the routine **xrt_cat.pro**.

In order to use this code, some ancillary XRT files are necessary and can be installed by running **sswdb_upgrade** from within SSWIDL and adding the **hinode** branch of the SSWDB tree.

### 2.2.1 Using xrt_cat.pro

This program returns XRT catalog records suitable for selecting data as a structure array. In the following example, the `ofiles` keyword generates a list of files using the subroutine **xrt_cat2files.pro**:

```
IDL> t0='2007-04-18T02:30:00'
IDL> t1='2007-04-18T12:30:00'
IDL> xrt_cat, t0, t1, catx, ofiles
IDL> help, catx
CATX STRUCT = -><Anonymous> Array[311]
IDL> help, ofiles
```

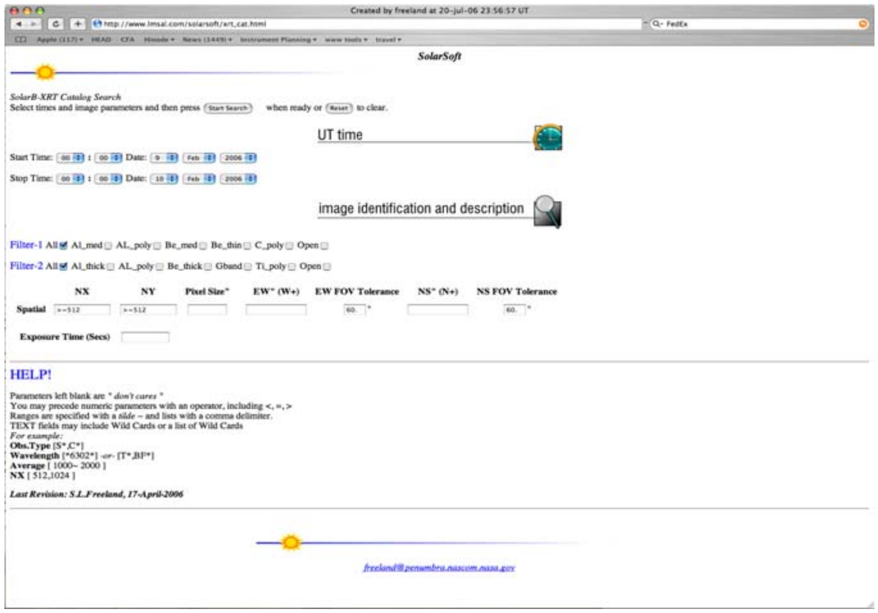



Figure 7: Downloading data

```
OFILES STRING = Array[311]
```

There are several input and output keywords that can be set to provide additional information.

Optional input keyword parameters:

1. `SEARCH_ARRAY`: (See **struct_where.pro**). Give a set of search parameters to further refine the data set.

2. `_EXTRA`: (Various possible types). Unknown parameters assumed to be in PARAM=VALUE pairs (see **struct_where.pro**).

3. `/URLS`: (Boolean) If set, then return `OFILES` as URLs to a remote data server. (Default is to give local full paths.)

4. `REFRESH`: (Boolean) If set, then refresh the cache (i.e., re-read the catalog).

5. `TEMP`: (Boolean) If set, then use a temporary (i.e., offline/in-progress) catalog database.

6. `/VERBOSE`: (Boolean) If set, print out extra information. Overrides `/QUIET`. There are three levels of verbosity, in order of priority: (1) `VERBOSE` displays all errors and messages. (2) `QUIET` suppresses all errors and messages. (3) No keyword displays all errors and some messages.

7. `/QUIET`: (Boolean) If set, suppress messages.

8. `/QSTOP`: (Boolean) For debugging.

Optional output keyword parameters:

1. `OFILES`: (string array, $[N_{img}]$) List of full path filenames for the Level 0 data matching the catalog. If `/URL`, then instead returns data paths to a remote data server. This list is generated by a call to the program **xrt_cat2files.pro**.

2. `ERROR`: (scalar number) Returns the `ERROR` keyword value from a call to **read_genxcat.pro**.

3. `QABORT`: (Boolean) Indicates that the program exited gracefully without completing. (Might be useful for calling programs.) 0: Program ran to completion. 1: Program aborted before completion.

### 2.2.2 Search criteria used to select XRT data

Further searching of XRT data can be done at the IDL command line using FITS keywords. All FITS values are in uninterpreted binary, with the exception that enumerated values are sometimes represented by string values instead of an integer. XRT follows with standard FITS file naming conventions, available at `http://fits.gsfc.nasa.gov`.
The following FITS file keywords may be of use.

1. `EC_IMTY_` : Image type; input string values of 'dark' or 'normal'.

2. `EC_FW1_` : Filter Wheel 1 position; input string values of 'Open', 'Al_poly', 'C_poly', 'Be_thin','Be_med', 'Al_med'

3. `EC_FW2_` : Filter Wheel 2 position; input string values of 'Open', 'Al_poly', 'Ti_poly', 'Gband,' 'Al_thick', 'Be_thick'

4. `EC_VL_` : Visible light shutter position; input string values of 'open' or 'closed'.

5. `NAXIS1` : General FITS keyword for pixel length in the $x$-direction; input integer value. XRT images are generally 512×512, 1024×1024 or 2048×2048; though any given area of the CCD can be read out.

6. `NAXIS2` : General FITS keyword for pixel length in the $y$-direction; input integer value.

Basic filter example:

```
IDL>ss=where(catx.ec_imty_ eq 'normal' and catx.naxis1 eq 512)
```

The following keywords are not useful for searching purposes, but are quite useful for interpretation purposes:

1. `EXPTIME` : This keyword represents the duration of the CCD exposure for normal images in seconds. `EXPTIME` is useful for sorting long/short pairs.

2. (`DATE_OBS` + `DATE_END` / 2): Performing this calculation best represents the UT time the exposure was taken.

## 2.3 Reading XRT Data

### 2.3.1 Using read_xrt.pro

All XRT image headers and data can be read using the IDL routine **read_xrt.pro**, which calls the subroutine **mreadfits.pro**. Because XRT images are of various sizes, **read_xrt.pro** can read header and data information for images of various sizes using the keyword `/force`. If the `/force` keyword is used to read image data of various sizes, the data array will be given the maximum required dimensions. Smaller images will be embedded in the lowest corner of the respective 2D slice, with zero values in the buffer pixels. These small images will retain their original `NAXIS1` and `NAXIS2` keywords; for example, if a 512×512 image is embedded in a 2048×2048 array, the `NAXIS1` and `NAXIS2` keywords for that image will read 512 and 512, respectively.

Basic call, to read headers and data:

```
IDL> ss=where(catx.ec_imty_ eq 'normal')
IDL> read_xrt, ofiles[ss], index, data
IDL> help, ofiles
OFILES STRING = Array[5]
IDL> help, index
INDEX STRUCT = -><Anonymous> Array[5]
IDL> help, data
DATA INT = Array[2048, 2048, 5]
```

To read headers and data for images of various sizes:

```
IDL> read_xrt, ofiles, index, data, /force
```

To suppress messages from mreadfits.pro:

```
IDL> read_xrt, ofiles, index, data, /force, /quiet
```

To display extra information:

```
IDL> read_xrt, ofiles, index, data, /force, /verbose
```

The `index.History` keyword is updated to reflect the origin file of the data:

```
IDL> print, index[0].History
READ_XRT v2007-May-09:  (22-May-2007 17:56:30) Read header only.
Origin file:  XRT20070417_000216.4.fits
```

## 2.4 Calibrating XRT Data

### 2.4.1 Using xrt_prep.pro

The routine **xrt_prep.pro** is similar in nature to **trace_prep.pro**, **eit_prep.pro** and **sxt_prep.pro**. The routine is intended to convert Level 0 data to Level 1 data. This process adds additional keywords to the Level 1 data FITS header. It is important to note that if images of different sizes were read in using **read_xrt.pro**, the values for the `NAXIS1` and `NAXIS2` keywords are preserved while running **xrt_prep.pro**.

Basic call:
`IDL> XRT_PREP, input1, input2, index_out, data_out`, where `input1` and `input2` can take on one of two different values:

*Case 1*
Input 1: XRT FITS file list as a string scalar or array.
Input 2: The data set number(s) to extract and process.

*Case 2*
Input 1: The index structure for the file list as a structure array.
Input 2: The data array(s) as an integer array.

The basic calls for each case:
*Case 1*:

```
IDL> ss = where(catx.ec_imty_ eq 'normal')
IDL> xrt_prep, ofiles[ss], dset_arr, index_out, data_out
IDL> help, ofiles
OFILES STRING = Array[5]
IDL> help, dset_arr
DSET_ARR LONG = Array[4]
IDL> help, index_out
INDEX_OUT STRUCT = − ><Anonymous> Array[4]
IDL> help, data_out
DATA_OUT FLOAT = Array[2048, 2048, 4]
```

*Case 2*:

```
IDL> xrt_prep, index, data, index_out, data_out, dark=dark
IDL> help, index
INDEX STRUCT = − ><Anonymous> Array[5]
IDL> help, data
DATA INT = Array[2048, 2048, 5]
IDL> help, index_out
INDEX_OUT STRUCT = − ><Anonymous>Array[5]
IDL> help, data_out
DATA_OUT FLOAT = Array[2048, 2048, 5]
```

The routine will output the updated index structure of the input images as a structure array $[N_{img}]$ and processed output images as an integer array $[N_x, N_y, N_{img}]$.

The executed steps, in chronological order:

1. Read in raw FITS image(s) from a filelist or read in a datacube and structure.
2. Fill pixels of value = 0 with mean pixel value of entire image.

3. Replace near-saturated pixels for values > 2500 DN with 2500 DN.
4. Option to remove radiation-belt/cosmic-ray hits and streaks (using the subroutine **xrt_clean_ro.pro**).
5. Calibrate for read-out signals.
6. Remove the CCD bias (pedestal).
7. Calibrate for the dark current.
8. Option to normalize each image for exposure time.
9. Output the corrected image(s) in an updated structure and data cube.

There are several input and output keywords that can be set to provide additional information.

Optional input keyword parameters:

1. `/NO_DARKSUB`: (Boolean) Set to not perform dark subtraction.
2. `/DESPIKE`: (Boolean or integer) Set if 1 pass of unspike wanted to remove radiation-belt and/or cosmic-ray spikes, or set to 1-3 passes of unspike. This method uses convolution and thresholding to remove spikes and may remove small real features and/or reduce the overall sharpness of the image.
3. `/NORMALIZE`: (Boolean) Set to normalize output image to DN per sec.
4. `/FLOAT`: Set if you want to return floating point. (Default is I*2).
5. `/QUIET`: (Boolean) Set for no messages or errors.
6. `/VERBOSE`: (Boolean) Set for all messages, errors, and intermediate data listings. Suppresses quiet.
7. `/QSTOP`: (Boolean) For debugging.

Optional output keyword parameters:

1. `MISS_MAP`: (byte array, $[N_x, N_y, N_{img}]$) This is a 2D Boolean map of each image. 0: Image pixel had data. 1: Image pixel was missing data and was replaced with the image average.
2. `N_MISS_PIXEL`: (long array, $[N_{img}]$) Number of missing pixels found in each image.
3. `SAT_MAP`: (byte array, $[N_x, N_y, N_{img}]$) This is a 2D Boolean map of each image. 0: Image pixel was not saturated. 1: Image pixel was saturated and was replaced with a constant value of 2500 DN.
4. `N_SAT_PIXEL`: (long array, $[N_{img}]$) Number of saturated pixels found in each image.
5. `RUN_TIME`: (float scalar) The run time in seconds for **xrt_prep.pro**.
6. `QABORT`: (Boolean) Indicates that the program exited gracefully without completing. (Might be useful for calling programs.) 0: Program ran to completion. 1: Program aborted before completion.

### 2.4.2 Routines used by xrt_prep.pro

**XRT_CLEAN_RO.PRO** An XRT image shows a prevelent sinusoidal ringing in $x$ at the Nyquist frequency, with a peak-to-peak amplitude of $\approx 2.6$ DN. There is also a low-level large-scale "ski-ramp" in $y$ with a shape which can be approximated by an exponential decrease (amplitude $\approx 4.3$ DN, $e$-folding width $\approx 185$ pixels) and a weak linear increase on a base of $\approx$ 42 DN, which is best seen in dark frames. The Fourier transform of an XRT dark shows many odd features, including "streaks" (narrow ridges of power spanning all $y$; many are semi-fixed in location), 2-D Voigt profiles, and truncated streaks. The latter two features are typically variable in $y$ position; all vary in amplitude. These features are present (though less clearly visible) in the Fourier transform of data as well. The routine **xrt_clean_ro.pro** attempts to correct for these read-out signals, while introducing no artifacts of its own.

The procedure removes the nyquist ringing (using **no_nyquist.pro**), the large-scale "ramp" (using **lsback_away.pro**), and the Fourier features (using **xrt_fourier_vacuum.pro**), in that order. The Fourier filtering can take a while on large images ($\approx$15 seconds on a 2048$\times$2048 pixel image using a MacPro with dual 3GHz Xeon chips). Low frequencies on the transform are shielded from correction to avoid damaging the data; thus some low frequency read-out components will remain. The basic call is as follows:

```
IDL> xrt_clean_ro,image_in,image_out,hist=hist
```

Sometimes, the the default parameters cause the routine to correct some parts of the transform which contain a non-negligible data component in the Fourier power. In these cases, the read-out signals can be over-corrected. This can cause sinc "ringing" around bright features in the corrected image. To reduce this, one can experiment with increasing the threshold for Fourier feature removal (`nsigma` [default=4.5]) and/or decreasing level above background in Fourier space to begin data shielding (`nmed` [default=3.5]). For example:

```
IDL> xrt_clean_ro,image_in,image_out,hist=hist,nsigma=5.0,nmed=3.0
```

It may also be useful to experiment with the form of the Fourier analysis by changing clean_type. For example:

```
IDL> xrt_clean_ro,image_in,image_out,hist=hist,clean_type=1,nsigma=5.0,nmed=3.0
```

**XRT_UNSPIKE.PRO** In this routine, bright pixels are first amplified, then located by convoluting them with a simple kernel. All pixels above a certain threshold are identified as spikes, and are duly replaced. Note that this routine will artificially alter the value of pixels in the image.

Basic call, where the keyword `/cleanjpg` calls the routine **xrt_cleanjpg.pro**:

```
result = XRT_UNSPIKE(image_in [,sens=sens] [,/cleanjpg])
```

## 2.5 Displaying XRT Data

XRT has a large dynamic range. To display the data using IDL, it is often useful to logarithmically scale the data. If viewing a 2048×2048 image, which does not fit on most computer screens, it may be useful to rebin the image.

```
IDL> wdef, 512
IDL> loadct, 3; To load the red color table in SSWIDL
IDL> data_dp = data - 42; Remove the pedestal, which is ≈ 42 DN, for Level 0 data
IDL> data_pos = (data_dp > 0); To create an array of positive values
IDL> new_data = rebin(data_pos, 256, 256); To rebin the image
IDL> tv, bytscl(alog(new_data[*,*,0]))
```

## 2.6 Co-aligning XRT Data

In progress.

## 2.7 Making long-short composite images with XRT Data

### 2.7.1 Using xrt_auto_image.pro

In progress.

## 2.8 Making movies with XRT Data

Movies of XRT data can be made using a combination of IDL and software capable of stringing together a series of images, such as QuickTime Pro.

First, display the data on the screen (see Section 2.5, Displaying XRT Data). XRT movies are made by capturing images displayed on the monitor using the IDL function **tvrd**, which works in similar fashion to a screen-shot function. For this reason, image quality is dependent on the resolution of your computer monitor. To avoid this problem, port images into the IDL Z-buffer and read them from there:

```
IDL > set_plot, 'Z'
IDL > device,set_r = [512,512]
```

After determining the size of the data array, a movie can be made using a simple for loop:

```
IDL > help, data_out
DATA_OUT INT = Array[512, 512, 64]
IDL > for i=0, 63 do begin &
IDL > tv, bytscl(alog(data_out[*,*,i])) &
IDL > xyouts, 0.03, 0.03, index[i].date_obs, /normal, size=2.0 &
IDL > opf = 'Hinode_XRT'+trim(i,'(i3.3)')+".png" &
IDL > print, 'Saving image as:  ', opf &
IDL > write_png, opf, tvrd(), red, green, blue &
IDL > endfor
```

Generate a movie using software capable of stringing together a sequence of images.

## 2.9 Writing XRT Data

### 2.9.1 Using write_xrt.pro

This program will write Level 1 FITS files for the input data (unless the `PATHS_ONLY` switch is used). There will be one image per file. By default, the files will be written into the current working directory, but file-paths can be modified with keywords.

Examples:
Basic call, to write to a user-specified directory:
```
IDL> write_xrt,index_out,data_out,outdir='/home/user/'
```

Write Level 1 data-cube into the site XRT archive:
```
IDL> write_xrt, index_out, data_out, /archive
```

Get the output filenames without writing the files:
```
IDL> write_xrt, index_out, data_out, /paths_only, out_paths
```

Optional input keyword parameters:

1. `/ARCHIVE`: (Boolean) If the `/ARCHIVE` switch is used, then the standard archive path and standard filename format will be followed. This overrides `OUTDIR` and `OUTFILE`. If `/ARCHIVE` is not used, then `OUTDIR` and `OUTFILE` are used if they are given. If `OUTDIR` is not given, then the current working directory is used. If `OUTFILE` is not given, then standard format filenames are used. The `OUTDIR` and `OUTFILE` keywords operate independently. If they are both given, then `OUTDIR+OUTFILE` will be used.

2. `OUTDIR`: (string scalar) Specifies the fully qualified output directory. Default = the current working directory. `OUTDIR` overrides `ONLINE`.

3. `OUTFILE`: (string array, $[N_{img}]$) Specifies the output filenames. Default = follow the XRT filename standard for Level 1 FITS files: L1_XRTyyymmdd_hhmmss.s.fits

4. `/PATHS_ONLY`: (Boolean) If set, just return `OUT_PATHS` but don't write any files.

5. `/MAKE_DIR`: (Boolean) If set, create implied directories if they do not exist.

6. `/VERBOSE`: (Boolean) If set, print out extra information. Overrides `/QUIET`

7. `/QUIET`: (Boolean) If set, suppress messages.

8. `/QSTOP`: (Boolean) For debugging.

Optional output keyword parameters:

1. `OUT_PATHS`: (string array, $[N_{img}]$) List of implied/derived full file-paths for the output.

2. QABORT: (Boolean) Indicates that the program exited gracefully without completing. (Might be useful for calling programs.) 0: Program ran to completion. 1: Program aborted before completion.

#### 2.9.2 Using write_png.pro or write_bmp.pro:

Furthermore, IDL routines will write out lossless image files (such as BITMAP) and lossy images files (such as PNG):

```
IDL> loadct, 3
IDL> tv, bytscl(alog(data_out[*,*,0])
IDL> write_png, tvrd(), red, green, blue, or
IDL> write_bmp, tvrd(), red, green, blue
```

### 2.10 Temperature Analysis with XRT Data

In progress.

## 3 X-Ray Telescope Instrument Guide

### 3.1 Telescope Overview

The XRT includes a single Wolter I X-ray optic and a companion visible light optic. The optics are supported at one end of a telescope tube. At the opposite end are two filter wheels with analysis filters, the main shutter, and a camera. There is an additional set of heat rejection filters in front of the optics, and a visible light shutter that allows light through the visible light optic. A focus mechanism controls the spacing between the optical elements and focal plane.

The Mission Data Processor (MDP) coordinates the operation of the XRT and the CCD camera, in addition to the other components on the satellite. Camera image data is delivered directly to the MDP. The only electrical connection between the XRT and the camera is the CCD_EXPOSE line, which initiates an exposure.

#### 3.1.1 X-Ray Performance

| | |
|---|---|
| Focal Length | 2707.2 mm $\pm$ 0.3 mm |
| Aperture Size | 34.1 cm |
| Bandwith | 0.2 to 1.2 keV |
| Image Performance | 68% encircled energy within 27 micron at 0.523 keV at the focal plane |
| Field of View | $35.11' \times 35.11'$ |
| Visible Light Suppression | $10^{11}$ |
| Effective Area | $> 2.2$ cm$^2$ at 0.523 keV |

### 3.1.2 Optical Performance

| | |
|---|---|
| Focal Length | 2708 mm ± 5 mm (adjusted to focus at the X-ray focal plane) |
| Central wavelength | 4305Å ± 20Å (G-Band) |
| Bandpass | < 170Å FWHM |
| Resolution | < 2 arcsec half power diameter |
| Field of View | > 30 arcmin |
| Co-alignment | 17 arcseconds |
| Confocality with X-ray optic | ± 150 micron |

### 3.1.3 MDP/XRT Communications

Communication occurs using a set of discretes (MDP-to-XRT signals) and bilevels (XRT-to-MDP signals), as well as serial commands sent from the MDP and status packets sent from the XRT. Discretes and bilevels propagate essentially instantaneously on the time-scale of interest. Serial commands consist of status requests, regularly spaced at 500 ms intervals, and other commands, interspersed between status requests, that perform specific actions. Status requests act as a heartbeat, resulting in receipt of a similarly spaced stream of status packets.

## 3.2 CCD Camera

XRT uses a back-illuminated three-phase CCD with 13.5 $\mu$m pixel-size and 2048×2048 array, which was manufactured by E2V Technologies. The CCD has two identical read-out ports; R-port and L-port. XRT uses R-port as the default port, and L-port as a backup. From either port, an entire CCD image can be read. Characteristics of the camera are described in the table below.

| | |
|---|---|
| CCD Type | Back-illuminated CCD (E2V/CCD 42-40) |
| Pixel Format | 2048×2048 pixels |
| Pixel Size | 13.5 $\mu m$ × 13.5 $\mu m$ |
| Field of View | 35×35 arcmin |
| Pixel Binning Mode | 1×1, 2×2, 4×4, 8×8 |
| Dark Current | 0.1 $e^-$/sec/pixel at -65°C |
| CCD Temperature | Passive cooling: $< -43$°C |
| CTE | Parallel > 0.999996, Serial > 0.999999 ($-93°C < T < -50°$ C) |
| QE (X-Ray/EUV) | 0.93 at 13Å, 0.61 at 45Å, 0.46 at 116Å, 0.56 at 304Å |
| QE (Visible Light) | 0.44 at 4000Å, 0.66 at 5000Å |
| Full-well capacity | $2.0\times10^5$ $e^-$ |
| Camera Gain Constant | 57 $e^-$/DN |
| Camera System Noise | < 30 $e^-$ |
| Output Data Resolution | 12 bit |

### 3.2.1 Pointing

Hinode can point anywhere on the solar disk. XRT, SOT and EIS planners decide on the day's pointing every morning. Hinode has four pointing tracks; thus it is not capable of tracking more than four objects over the course of one day.

XRT can offset its pointing from the spacecraft pointing using Region of Interest (ROI) tables. These tables allow the XRT Chief Observer to construct rectangular field of views, though the smallest scientifically valuable field of view is 256×256. The amount XRT can offset depends on the size of the image being read out from the CCD. If reading out a 256×256 image, XRT can offset up to 896 arcseconds from the Hinode pointing. Reading out images larger than 256×256 causes the offset amount to decrease. Reading out the full 2048×2048 CCD requires the XRT pointing to be equal to the spacecraft pointing.

Due to the position of the instrument on the spacecraft, XRT X-Ray image pointings are inherently offset from the spacecraft pointing. The XRT X-Ray images are offset from the SOT pointing by 40.0 arcseconds in the $x$-direction and 22.3 arcseconds in the $y$-direction. The XRT VLI images are offset from the XRT X-Ray images by 32.4 arcseconds in the $x$-direction and 42.3 arcseconds in the $y$-direction. These offsets vary in time due to the spacecraft orbit and jitter.

### 3.2.2 Exposures

XRT enables several algorithms to maximize the quality of observations. They are succinctly described below.

**Automatic Exposure Control** The Automatic Exposure Control (AEC) adjusts the exposure duration by analyzing the most recent X-ray image on board in a pipe-line manner. AEC is available only for the image with size smaller than or equal to 256 k pixels (i.e. a 512×512 pixel image). If an X-ray image does not achieve the proper exposure with the shortest exposure, AEC automatically changes the X-ray analysis filter to a pre-specified thicker filter.

**Automatic Region Selector** The Automatic Region Selector (ARS) is the function to automatically update ROI targets. This function does not work during the flare observation or during the passage of radiation belts. There are two functions in ARS. One is a global search to select the brightest region in the full frame of CCD and to update ROI1 table. The other is a local search to track a bright region by searching only around the current ROI location, and it updates ROI2, ROI3, and ROI4 independently.

**Flare Detection Algorithm** Because Hinode is not equipped with any dedicated X-ray detectors to detect solar flares, XRT has to do so by itself. The Flare Detection (FLD) is the function to detect the occurrence of a flare, to identify the flare location on CCD, and to raise a flare flag not only for XRT but also SOT and EIS. XRT takes full frame CCD images with 8 arcsec resolution (called FLD patrol images) at regular intervals. The intervals during the normal observation and during the flare observation can be set independently in the FLD Control Table. The baseline interval to take FLD patrol images is about 30 sec. Each FLD patrol image is first divided into 16×16 blocks, called macro-pixels. The macro-pixel image is created by summing the intensity in each macro-pixel. From a macro-pixel image, the MDP calculates a parameter which indicates the increase of the X-ray intensity normalized by the photon noise; if this parameter exceeds the threshold for the flare start in more than one macro-pixel, the MDP sets the flare flag and proceeds to calculate the flare position. When this parameter is smaller than the threshold for flare end, the MDP drops the flare flag.

## 3.3 XRT Mechanisms

The X-Ray Telescope is composed of entrance filters, mirror, focal plane filters, visible light shutter, visible light imager, focus mechanism, filter wheel and shutter assembly system. Detailed descriptions are available in the XRT User's Manual at `http://xrt.cfa.harvard.edu/MODA/`. Short descriptions of the mechanisms relevant to those proposing joint observing programs are included below.

### 3.3.1 Visible Light Shutter

The VLS is opened to admit visible light to assist in aiming the telescope and aligning X-ray images with optical images from the SOT, but must be closed during X-ray exposures. The fail-safe mode for the VLS is closed, since X-ray exposures can only be made with the visible light shutter closed. It passes no more than 10-10 of visible light when closed. A stepper motor opens (positive direction) or closes the shutter. Moving the shutter from open to closed requires about 165 steps.

### 3.3.2 Visible Light Imager

The visible light imager (VLI) is mounted in the center of the Sun shield. X-rays pass through and are focused by the ring near the edge of the Sun shield. Visible light passes through the visible light shutter, if it is open, then through the visible light imager, and to the camera CCD array.

### 3.3.3 Focus Mechanism

After calibration, a position of 0 places the mechanism in the middle of the range. In this position, there is no stress on the CCD array. The stepping rate is approximately 300 actual steps/s. It takes about 67 s to move from one extreme to the other. Each 200 steps of the stepping motor corresponds to a single revolution of the motor shaft, and 40,000 steps (200 revolutions) are necessary to complete a cycle of the geared down cam. One half cycle, 20,000 steps, moves the focus rod from one focus extreme to the other, a range of $\pm 2.433$ mm. This is converted to $\pm 1$ mm camera deflection. There is a magnetic detent every fourth step. For this reason, position tracking remains reliable over time only if positions are specified in multiples of four focus motor steps. A focus step is defined as four motor steps. The focus odometer counts motor steps.

### 3.3.4 Filter Wheel/Shutter Assembly (FSA) Subsystem

The FSA subsystem consists of two filter wheels and the focal plane shutter, and the associated controllers. The focal plane shutter (FPS) is a disk containing narrow, medium and wide slots, shown here with the motor behind. The narrow ($1.8^{\circ}$) and medium ($14.4^{\circ}$) slots are swept over

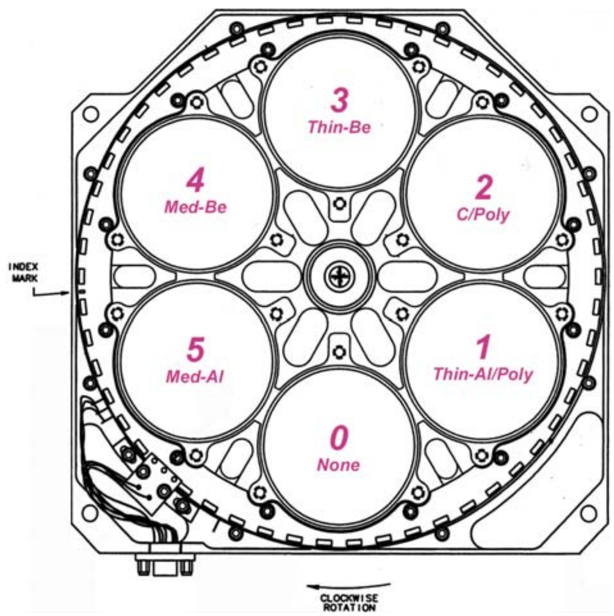



Figure 8: Filter Wheel 1

the camera aperture at a constant rate to make exposures. That is, the motor accelerates to a maximum speed before the slot is reached, then begins braking after the slot has passed. For wide (80°) exposures, the shutter may dwell in the open position as needed to complete the exposure. Thus the shutter brakes to a halt in the center of the wide slot, then reaccelerates to complete the pass. The shutter rotates either clockwise or counterclockwise to perform an exposure, so it is necessary to skip an intermediate slot only one third of the time. Exposure timing is somewhat asymmetric depending upon direction of motion. The shutter is not completely opaque to X-rays. The CCD is swept whenever it is not exposing to flush accumulated charge. A brushless DC motor operates the shutter. Timing marks placed at 20° intervals determine the resolution with which shutter position is known to the controller.

The FSA subsystem operates two independently-positioned filter wheels. Each filter wheel has six slots, one of which has no filter. The filters provide a temperature resolution of 0.2 log T, $6.1 < \log T < 7.5$. They are numbered as shown.

Filter wheels require nearly 1.5 s to switch between adjacent positions, and thus can make up the longest part of an expose cycle. To minimize positioning time, select exposure order to reduce motion and/or use the expose commands filter wheel pre-positioning. Filter wheels are positioned sequentially, not in parallel, so time is additive (though typically both filter wheels are not used in the same exposure).

## 3.4 XRT Instrument Response

The XRT instrument response is shown in Figure 10. Note that the instrument sensitivity changes by four orders of magnitude between the Al-mesh and Be-Thick filters.

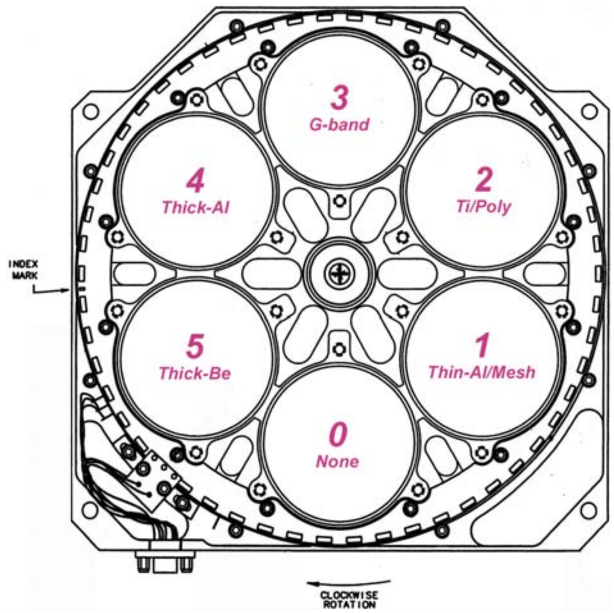



Figure 9: Filter Wheel 2

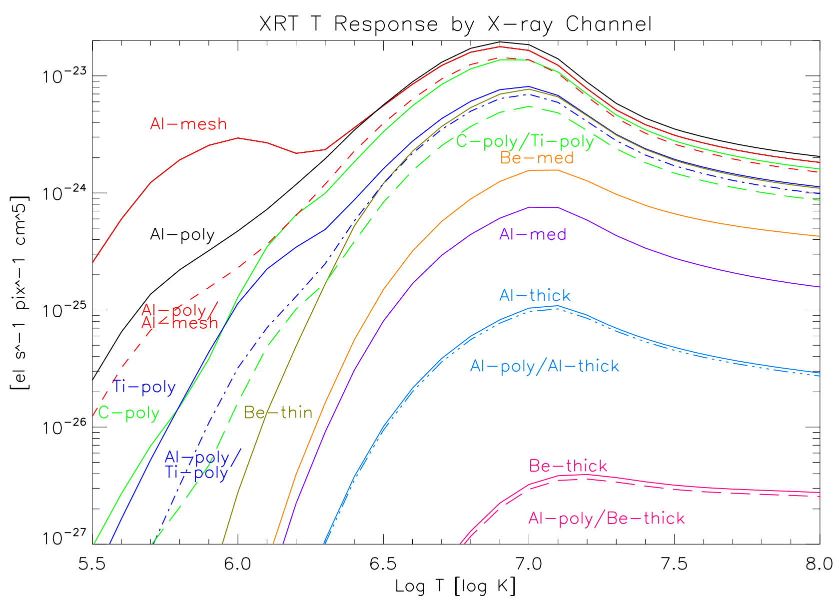



Figure 10: XRT Temperature Response

# A Level 0 Header Keywords

This appendix explains the 162 keywords in the XRT Level 0 FITS header.

| Keyword | Value | Definition |
|---|---|---|
| SIMPLE | T | Conforms to FITS standard |
| BITPIX | 8, 16, 32, -32, -64 | Number of bits per pixel |
| NAXIS | 2 | Number of axes in the image |
| NAXIS1 | | Full image size in $x$ |
| NAXIS2 | | Full image size in $y$ |
| DATE | 'YYYY-MM-DDThh:mm:ss.sss' | Date and time of file creation ('T' is character 'T') |
| DATE_RF0 | 'YYYY-MM-DDThh:mm:ss.sss' | Date and time of Level 0 reformatting ('T' is character 'T') |
| SATELLIT | 0x21 | Satellite number (from PDU header for images) |
| TELESCOPE | 'SolarB' | Derived from above |
| INSTRUME | 'XRT'; 'SOT/SP'; 'SOT/FG' | Name of the instrument; reformatter only retrieves XRT records |
| TIMESYS | 'UTC'; 'TAI' | Time system of file header |
| MDP_CLK | | MDP clock in units of $1/512^{th}$ seconds; same as E_SCLOCK |
| FILEORIG | | Original filename used by level 0 reformatter |
| P1ROW | 0 to N-1 | $x$-coordinate of beginning, or lower left hand corner, pixel in image FOV; same as RPOS_ROW |
| P2ROW | 0 to N-1 | $x$-coordinate of ending, or upper right hand corner, pixel in image FOV; same as RPOS_ROW + RSIZ_ROW - 1 |
| P1COL | 0 to N-1 | $y$-coordinate of beginning, or lower left hand corner, pixel in image FOV; same as RPOS_COL |
| P2COL | 0 to N-1 | $y$-coordinate of ending, or upper right hand corner, pixel in image FOV; same as RPOS_COL + RSIZ_COL - 1 |
| TR_MODE | 'TR1'; 'TR2'; 'TR3'; 'TR4'; 'FIX' | Tracking mode |
| IMG_MODE | 1-3 | Image mode (source of exposure trigger); 1: Table and manual, 2: Automatic Region Selection Patrol, 3: Flare Detection Patrol |
| AEC_FLG | 'off' ; 'on' | Automatic Exposure Control; 1: Off, 2: On |
| AEC_TNUM | | AEC table number; 0: Out of RB, 1: In RB |
| AEC_RSLT | 0-3 | Result of AEC calculation used to determine exposure time; 0: Normal, 1: Underexposure, 2: Overexposure, 3: No feedback |
| ORIGIN | 'ISAS; NAOJ; MSSL; LMSAL; GSFC; 'SAO | Origin of the Chief Observer |

| Keyword | Value | Definition |
|---|---|---|
| DATA_LEV | 0, 1 | Data Level; running **trace_prep.pro** will change 0 to 1 |
| ORIG_RFO | 'ISAS ; NAOJ ; MSSL ; LMSAL ; GSFC ; 'SAO | Where the level 0 file was created |
| VER_RFO | | Version of Level 0 reformatter |
| PROG_VER | 0-7 | MDP observation table program version number |
| SEQN_VER | 0-7 | OT sequence table version number |
| PARM_VER | 0-3 | OT parameter table version number |
| PROG_NO | | OT program number |
| SUBR_NO | | OT subroutine number being executed |
| SEQN_NO | | OT sequence table number |
| MAIN_CNT | 0-7 | OT number of times to repeat main loop |
| MAIN_RPT | | OT current main-routine iteration |
| MAIN_POS | | OT main-routine position |
| SUBR_CNT | | OT sequential number of this subroutine in the main routine |
| SUBR_RPT | | OT number of times current subroutine is repeated |
| SUBR_POS | | OT loop count for current subroutine |
| SEQN_CNT | | OT current sequence table repeat count |
| SEQN_RPT | | OT sequence table repeat count |
| SEQN_POS | | OT sequence table position |
| OBSTITLE | | Title of observation |
| TARGET | 'Active region' ; 'Quiet region' ; 'Coronal hole' ; 'Flare site' | Indicates the observation region. Flare site used when flare flag is set. Source of information observation planning database, or telemetry if flare flag is set. |
| SCI_OBJ | | Up to 5 target phenomena selected from list. See Mission-Wide Keywords document, p. 26. |
| SCI_OBS | | Target phenomena. |
| OBS_DEC | | A few sentences describing the properties of the observation. |
| JOIN_SB | 'ESX'; 'SX'; 'EX'; 'X' | Joint observation; E=EIS, S=SOT, X=XRT |
| OBS_NUM | | Equal to OBS_ID |
| JOP_ID | | Identifier of JOP |
| NOAA_NUM | | AR Number as assigned by NOAA |
| OBSERVER | | Name(s) of Chief Observer |
| PLANNER | | Name(s) of Chief Planner |
| TOHBANS | | Name(s) of Tohbans |
| DATATYPE | 'SCI'; 'ENG' | Science or engineering data; darks and flats are considered engineering data |
| SAA | 'In'; 'Out' | Indicates whether Hinode is in or out of a South Atlantic Anomaly region |

| Keyword | Value | Definition |
|---|---|---|
| HLZ | 'In'; 'Out' | Indicates whether Hinode is in or out of Hight Latitude Zone region |
| FLFLG | 'Flr'; 'Non' | Indicates if flare flag set or not |
| S_INSTRU | 4 | Instrument number |
| S_DAT_ID | 1-3, 5-7 | Type of status packet this record was created from: 0: Not used, 1: Normal status, 2: Normal and extended status, 3: Normal status and memory, 4: Not used, 5: Standard HDR only, 6: Extended status, 7: Memory |
| S_DAT_M | 0, 1 | 0: Transfer to Kagoshima Space Center (KSC) and Sagamihara Satellite Operation Center (SSOC); 1: Monitor only at KSC |
| S_SP_SIZ | 31-609 | Status packet size; maximum value is 609, including header. |
| EC_ID | 0-65535 | Unique identifier, 'main ID' |
| EC_INDEX | 0-35 | Redundant to EC_EINDE; consider this keyword obsolete |
| EC_EINDE | 0-35 | Exposure Index |
| EC_CD_MO | 0, 1 | Cadence mode |
| EC_CD_M_ | 'safe' ; 'fast' | Cadence mode as name |
| EC_IMTYP | 0, 1 | Image type; 0: Normal, 1: Dark (closed shutter) |
| EC_IMTY_ | 'normal' ; 'dark' | Image type; a dark is taken with the shutter closed |
| EC_FW1 | 0-5 | Filter Wheel 1 position |
| EC_FW1_ | 'Open' ; 'Al_poly' ; 'C_poly' ; 'Be_thin' ; 'Be_med' ; 'Al_med' | Filter Wheel 1 position as name |
| EC_FW2 | 0-5 | Filter Wheel 2 position |
| EC_FW2_ | 'Open' ; 'Al_poly' ; 'Ti_poly' ; 'Gband' ; 'Al_thick' ; 'Be_thick' | Filter Wheel 2 position as name |
| EC_VL | 0, 1 | Visible light shutter during exposure; 0: Closed, 1: Open |
| EC_VL_ | 'closed' ; 'open' | Visible light shutter during exposure as name |
| E_SCLOCK | | Spacecraft clock of most recent status request prior to arrival of exposure command |
| E_LCLOCK | 0-16777215 | Time at which exposure command processing began, local clock, converted to $\mu$s |
| E_SH_OPE | 0-16777215 | Time CCD_EXPOSE and OPENOUT signals were raised (low 24 bits), converted to $\mu$s |
| E_SH_CLO | 0-16777215 | Time CCD_EXPOSE and OPENOUT signals were lowered (low 24 bits), converted to $\mu$s |

| Keyword | Value | Definition |
|---|---|---|
| EXCCDEX | | Duration of CCD_EXPOSE in $\mu$s; this is the correct value to use for dark exposure times |
| OBT_TIME | | Spacecraft clock time when CCD_EXPOSE was raised; this is E_SH_OPE converted to spacecraft clock time |
| OBT_END | | Spacecraft clock time when CCD_EXPOSE was lowered; this is E_SH_CLO converted to spacecraft clock time |
| E_SH_POS | | Shutter encoder position |
| E_SH_WA | | Waiting position A |
| E_SH_WB | | Waiting position B |
| E_SH_WC | | Waiting position C |
| E_SH_CW | | Waiting clockwise exposure time |
| E_SH_CCW | | Waiting counterclockwise exposure time |
| E_VLO | 0, 1 | VLS open microswitch; 0: Off (VLS not fully open), 1: On (VLS fully open) |
| E_VLO_ | 'not fully open'; 'fully open' | State of VLS |
| E_VLC | 0, 1 | VLS closed microswitch; 0: Off (VLS not fully open), 1: On (VLS fully open) |
| E_VLC_ | 'not fully open'; 'fully open' | State of VLS |
| E_SH_ERR | 0, 1 | 0: No error, 1: Shutter command error |
| E_FW1_PO | | Filter Wheel 1 course position (internal diagnostic format) |
| E_FW1_ST | | Filter Wheel 1 status |
| E_FW2_PO | | Filter Wheel 2 course position (internal diagnostic format) |
| E_FW2_ST | | Filter Wheel 2 status |
| E_ETIM_E | | Exposure time (exponent); see also E_ETIM (Though the value for E_ETIM should be normalized if the data is normalized, E_ETIM_E should remain *unchanged* so the user can reconstruct the original exposure time.) |
| E_ETIM_M | | Exposure time (mantissa); see also E_ETIM (Though the value for E_ETIM should be normalized if the data is normalized, E_ETIM_M should remain *unchanged* so the user can reconstruct the original exposure time.) |
| E_ETIM | | Exposure time in $\mu$s, derived from above two fields; this number should be normalized if the data is normalized by exposure time |
| EXPTIME | | Requested exposure time in seconds (calculated from EC_EINDE and exposure table) |
| E_TTN | | Rev. number of exposure table |

| Keyword | Value | Definition |
|---|---|---|
| EXPMPAS | 'single'; 'multi' | Single or multipass exposure |
| E_FW1_P | 'Open'; 'Al_poly'; 'C_poly'; 'Be_thin'; 'Be_med'; 'Al_med' | Filter Wheel 1 position |
| E_FW2_P | Al_poly'; 'Ti_poly'; 'Gband'; 'Al_thick'; 'Be_thick' | Filter Wheel 2 position |
| CCD_TEMP | | CCD temperature; $t_c = -95.853 + 0.55376 t_{raw} + 5.9941 \cdot 10^{-5} t_{raw}^2$ |
| CCD_TMPC | | CCD temperature, derived from CCD_TEMP |
| CCD_READ | 0, 1 | CCD readout port; 0: right, 1: left |
| READPORT | 'L'; 'R' | CCD readout port |
| CHIP_SUM | 1, 2, 4, 8 | On-chip pixel summation for CCD; 1: 1×1, 2: 2×2, 3: 4×4, 4: 8×8 |
| CAL_INFO | 0, 1 | CCD image type; 0: Calibration image, 1: Observation image |
| CALIMAGE | 'CAL' ; 'OBS' | CCD readout port (from CAL_INFO) |
| POS_COL | | CCD column number of start of image (original value multiplied by 8 to get number of pixels) |
| POS_ROW | | CCD row number of start of image (original value multiplied by 8 to get number of pixels) |
| ROI_H_SI | | ROI horizontal size; 1: 64, 2: 128, 3: 192, 4: 256, 6: 384, 8: 512, 12: 768, 16: 1024, 24: 1540, 32: 2048; (original value multiplied by 64 to get number of pixels) |
| SIZ_COL | | Horizontal size of ROI, derived from above; value is 0 if ROI_H_SIZE is reserved |
| ROI_V_SI | | ROI vertical size; 1: 64, 2: 128, 3: 192, 4: 256, 6: 384, 8: 512, 12: 768, 16: 1024, 24: 1540, 32: 2048; (original value multiplied by 64 to get number of pixels) |
| SIZ_ROW | | Vertical size of ROI, derived from above; value is 0 if ROI_V_SIZE is reserved |
| RECTIFY | | Status of rectification to put solar south-east corner at the start of the CCD image |
| RPOS_COL | | The rectified coordinate, equivalent to POS_COL, as though the image had been read out with this coordinate. If READPORT=R, RPOS_COL=POS_COL; otherwise RPOS_CPOS_COL. |
| RPOS_ROW | | Rectified POS_ROW. Always the same as POS_ROW. |
| RSIZ_COL | | Rectified SIZ_COL. Always the same as SIZ_COL. |

| Keyword | Value | Definition |
|---|---|---|
| RSIZ_ROW | | Rectified SIZ_ROW. Always the same as SIZ_ROW. |
| EFFPORT | | Rectified readout port |
| FOC_POS | -2500 to 2500 | Focus position |
| BITCOMP1 | | Compression table keyword |
| IMGCOMP1 | | Compression table keyword |
| QTABLE1 | | Compression table keyword |
| BITC_VER | 2 | Bit compression lookup table version |
| ACHF_VER | 76 | AC Huffman table version |
| DCHF_VER | 15 | DC Huffman table version |
| QTAB_VER | 0-7 | Quantization table version |
| PCK_SN0 | | Data packet keyword |
| PCK_SN1 | | Data packet keyword |
| NUM_PCKS | | Data packet keyword |
| HKTSYNC | | True if fields derived from housekeeping data have been updated. (That is, they are not missing from the database.) Default is false. |
| DATE_OBS | 'YYYY-MM-DDThh:mm:ss.sss' | UTC time when exposure began ('T' is character 'T') |
| TIME-OBS | 'hh:mm:ss.sss' | Same value as DATE_OBS, but in a different format |
| CTIME | 'DOW MON DD hh:mm:ss YYYY' | Example: 'Mon Mar 19 00:02:11 2007'; Same value as DATE_OBS, but in a different format |
| DATE_END | 'YYYY-MM-DDThh:mm:ss.sss' | UTC time when exposure began ('T' is character 'T') |
| CRPIX1 | | Column number of Sun center pixel (sometimes negative) |
| CRPIX2 | | Row number of Sun center pixel (sometimes negative) |
| SC_ATTX | | Spacecraft attitude in *longitude* |
| SC_ATTY | | Spacecraft attitude in *latitude* |
| CRVAL1 | 0.0 | Number of arcseconds of the center of the sun from the reference position in the azimuthal direction (E-W); positive is to Solar West |
| CRVAL2 | 0.0 | Number of arcseconds of the center of the sun from the reference position in the elevation direction (N-S); positive is to Solar North |
| CDELT1 | | Horizontal pixel size (PLATESCALE × SUMROW) |
| CDELT2 | | Vertical pixel size (PLATESCALE × SUMCOL) |
| CUNIT1 | | Horizontal units |
| CUNIT2 | | Vertical Units |
| CTYPE1 | | Type of units (label) of horizontal axis |

| Keyword | Value | Definition |
|---|---|---|
| CTYPE2 | | Type of units (label) of vertical axis |
| SAT_ROT | | Difference between Solar north and $y$-axis of the satellite |
| INST_ROT | | Difference between spacecraft $y$-axis and image $y$-axis |
| CROTA1 | | Angle between $x$-axis of image (same as $x$-axis of CCD) and E-W axis of heliocentric coordinates (SAT_ROT + INST _ROT) |
| CROTA2 | | Angle between $y$-axis of image and N-S axis of heliocentric coordinates (SAT_ROT + INST_ROT); CROTA1 and CROTA2 are identical for XRT |
| XCEN | | $X$-coordinate of center of field of view |
| YCEN | | $Y$-coordinate of center of field of view |
| XSCALE | | Same as PLATESCL |
| YSCALE | | Same as PLATESCL |
| FOVX | | Width of field of view $x$-axis; equivalent to NAXIS1 × CDELT1 |
| FOVY | | Width of field of view $y$-axis; equivalent to NAXIS2 × CDELT2 |
| PLATESCL | | Platescale, in units of arcseconds per pixel |